JPL

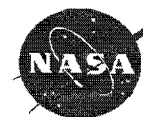## High Density Holographic Memory

Presented to

Int'l Symposium on Optical Memory

Presented by

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Objectives and Performance Specifications

- ## Objectives :
  - **Develop innovative memory technologies to enable large-capacity, high-speed, read/rewrite of image and digital data in a space environment**
  - **Demonstrate key capabilities:**
    - > Ultra High data/image storage capability (1TB)
    - > High-speed random access data transfer (1GB/s)
    - > Radiation-resistance

- Performance Specifications
  - **A compact holographic data storage with 10 GB non-volatile random access memory per cube**
  - **Up to 10 x 10 cubic memory can be stacked into an ordinary memory board size to achieve a storage capacity of 1TB**
  - **Read/rewrite, rad hard, high transfer rate**
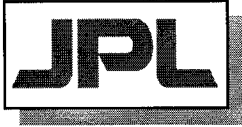
Holographic Memory Light Budget

GOAL: Video-rate recording with storage capacity of 10,000 pages of 1,000x1,000 gray-scale images.

List of materials available for this application

	LiNbO$_3$ Fe	LiNbO$_3$ Fe, Mn	LiNbO$_3$ Cr, Cu	Green Polymer *	Red Polymer *	PMMA Polymer
thickness	√	√	√			√
shrinkage	no	no	no	yes (3%)	yes (3%)	yes (2%)
wavelength	488nm	red+UV	red+blue	532nm	630-670nm	488nm
need fixing	yes	no	no	no	no	no
dynamic range	large	large	large**	modest	modest	modest
wiring speed	slow	very slow	slow**	very fast	fast	fast
rewritable	yes	yes	yes	no	no	no

* Thin materials only. Large-scale storage might be problematic with non-mechanical scanners.

** Projected.

For non-volatile storage of 10,000 holograms, the target diffraction efficiencies are,

$$\eta_h = \left(\frac{M/\#}{M}\right)^2$$

	$LiNbO_3$ Fe	$LiNbO_3$ Fe, Mn	$LiNbO_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
M/#	10*	10	30**	6	5	5
η_h	2.5×10^{-7}	10^{-6}	10^{-5}**	3.6×10^{-7}	2.5×10^{-7}	2.5×10^{-7}

* The M/# drops approximately by a factor of 2 after thermal fixing in $LiNbO_3$:Fe.
** Projected value.
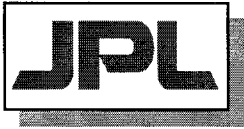
Light Budget Estimate

1. Photon-limited readout:

$$N_e = \eta_{tr} \eta_q \frac{\eta_h \eta_{im} P_{in}}{h\nu} \frac{1}{r_{ON} N_p} t_{int}$$

Variable	Definition	Value
Ne	number of signal electrons	~25,000*
η_{tr}	electron transfer efficiency	0.9**
η_q	quantum efficiency	0.9
η_h	hologram diffraction efficiency	**From above**
η_{im}	efficiency of readout optics	0.9
P_{in}	readout power	?
$h\nu$	power per electron	4.073×10^{-19} J
$r_{ON} N_p$	number of ON pixels	0.5×10^6 ***
t_{int}	integration time	1 sec.

* For binary data, 100 photoelectrons at a pixel are needed for optimal hard thresholding, considering electronic, optical, and holographic noise.

** Worst-case transfer efficiency from CCD to external electronics.

*** Exact number for binary random-bit patterns.
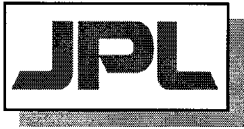
Readout powers for 1-second integration time

* Projected value

	LiNbO$_3$ Fe	LiNbO$_3$ Fe, Mn	LiNbO$_3$ Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
P$_{in}$ (mw)	28	7	0.07*	19	28	28

Recording speed

1. recording speed for 10,000 holograms (target diffraction efficiency is 10^{-7}).

	LiNbO3 Fe	LiNbO3 Fe, Mn	LiNbO3 Cr, Cu	Green Polymer	Red Polymer	PMMA Polymer
Writing energy mJ/cm^2	3	100*	1**	0.1	1	1
Writing intensity mw/cm^2	100	333*	33**	3.3	80	80

* For recording at He-Ne line. Data for blue recording is not available at the moment.
** Projected value.

System Schematic of an
Advanced CHDS Architecture

Photodetector
Array

Laser
Diode

Data
SLM

Laser Diode

Beam
Steering
LC SLM

Beam
Steering
LC SLM

Photorefractive
Crystal

Write Module

Read Module
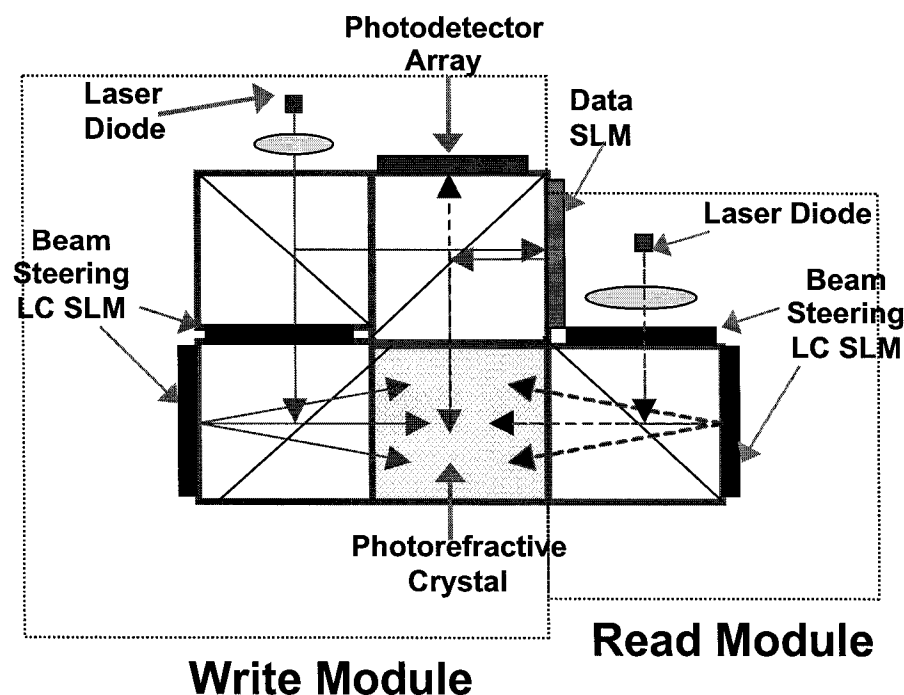
Unique Advantages

- **Very compact**
  - Cubic package with the size of a cigarette box

- **Massive data storage**
  - store up to 10^4 pages of hologram with 10 Gbytes capacity

- **High-speed**
  - current throughput 200 Mbytes/sec achieved with using a LC Beam Steering Device. Could be 10x faster if FLC is used

- **Device/components maturity**
  - Use two single diode lasers that are commercially available at low cost
  - Beam Steering Device is a emerging technology. JPL is actively engaged with BNS in developing the next generation high-speed version
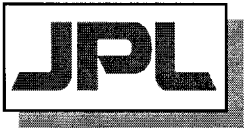
Liquid crystal phased array beam steering device

- Beam steering based on optical phase modulation
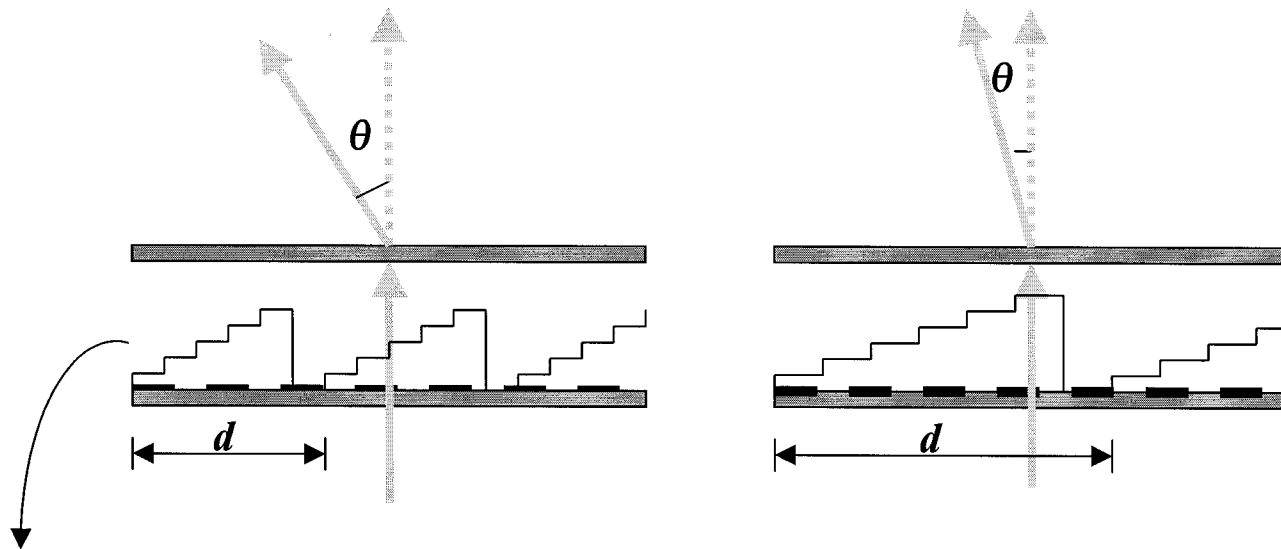
Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-2π ramp w/ a period d which determines the deflection angle θ
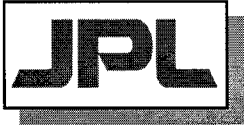
Liquid crystal phased array beam steering device

- **Diffraction efficiency:**

$$\eta = \left(\frac{\sin(\pi/n)}{\pi/n} \right)^2$$

n: number of steps in the phase profile

e.g., $\eta \sim 81\%$ for $n = 4$, $\eta \sim 95\%$ for $n = 8$

- **Deflection angle:**

$$\theta = \sin^{-1}(\lambda/d)$$

for the first order diffracted beam

- **Number of resolvable angles:**

$$M = 2m/n + 1$$

m: pixel number in a subarray
n: minimum phase steps used

e.g., $M = 129$ for $m = 512$, $n = 8$ with a 1x4096 beam steering device

9

Photograph of a Liquid Crystal Beam Steering Device
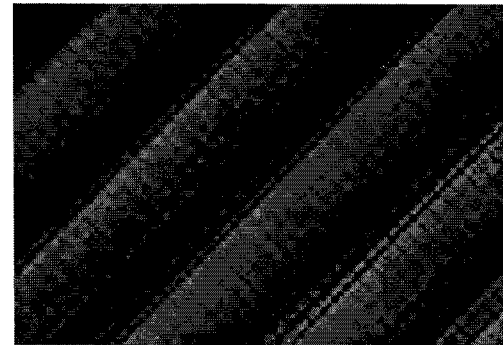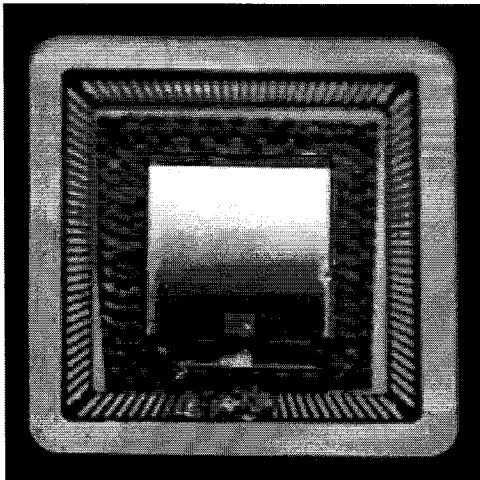
**Surface phase-modulation profile
of a beam steering device**
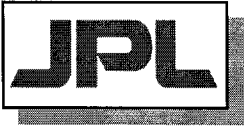
LabVEW Based Controller for Beam Steering

- Use LabVIEW to calculate the theoretically correct beam steering profile (I.e. sawtooth wave).

- Optimize the diffractive efficiency and suppress the spurious high orders

- A hardware-in-the-loop routine has been developed to customize the driving voltage for each and every beam deflection angle

- A nonlinear waveform of the driving voltage profile is obtained for good performance
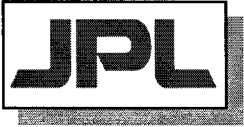
Sawtooth Profile

- The resulting profile (using an input value or N* of 57):
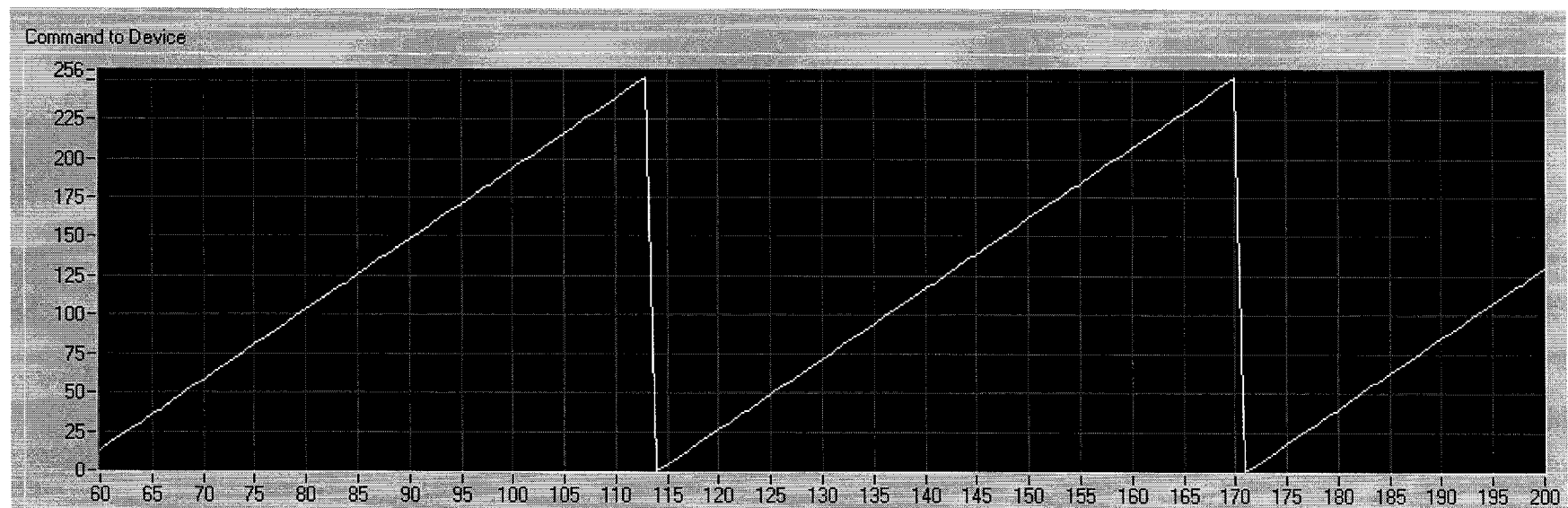
*The input value is proportional to the number of gratings on the device.
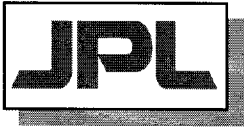
Tangent Profile

- For optimal results, parameters must be chosen such that the entire range of 0-256 is used with 0 and 256 occurring with a consistent period.
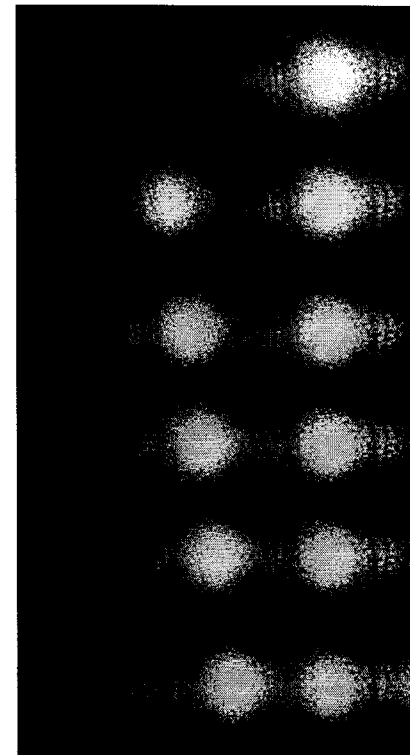- The selected parameters are unique for each angle.
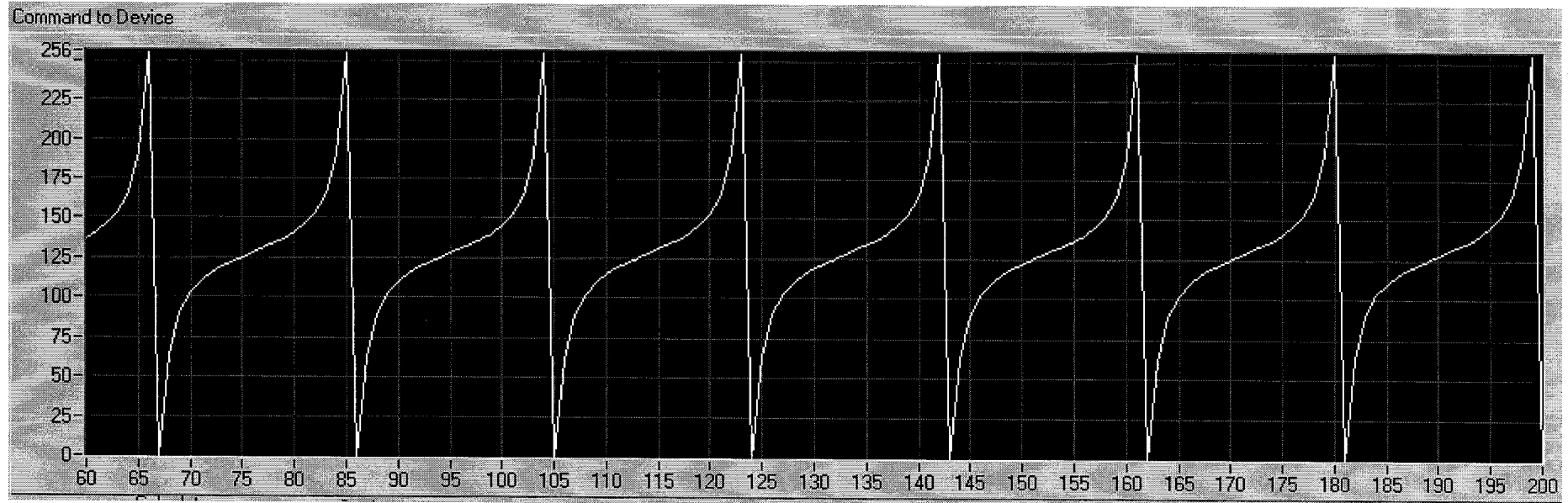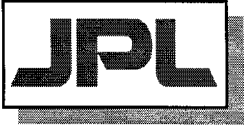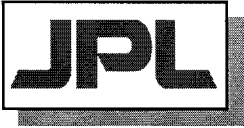
Resulting Diffraction Patterns

- The spurious higher orders of diffraction are nearly eliminated by using the nonlinear voltage driving waveform to the liquid crystal BSSLM
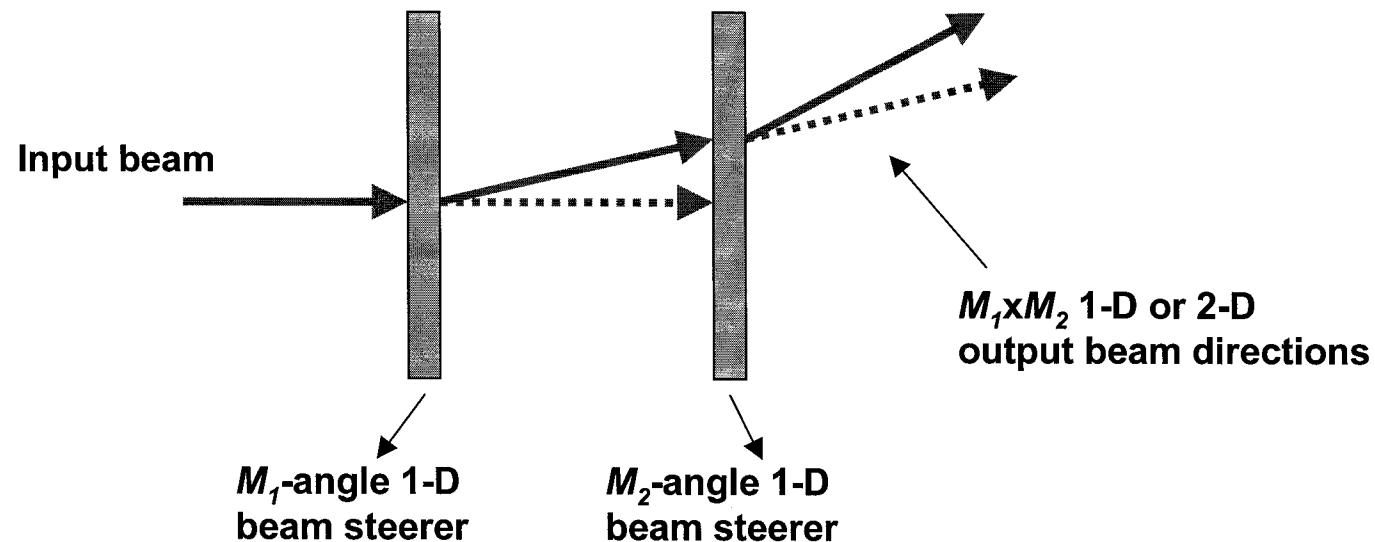
Device Off

Increasing

N

Liquid crystal phased array
beam steering device

- Cascaded beam steering architecture:

Input beam

$M_1 \times M_2$ 1-D or 2-D
output beam directions

M_1-angle 1-D
beam steerer

M_2-angle 1-D
beam steerer

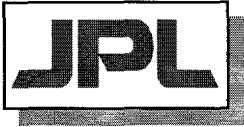**A total resolvable angels of more than 10,000 can be easily achieved.**

Liquid crystal phased array beam steering device

- **Benefits of using LC SLM beam steering devices:**

  - No mechanical moving parts

  - Randomly accessible beam steering

  - Low voltage / power consumption

  - Large aperture operation

 - No need for bulky frequency-compensation optics as in AO based devices
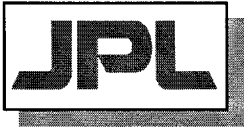
Performance Characteristics of
LC Beam Steering Device

- **Number of pixels: 4096 Reflective**

- **VLSI backplane in ceramic PGA carrier**

- **Array size: 7.4 x 7.4 mm**

- **Pixel size: 1µm wide by 7.4mm high Pixel pitch: 1.8 µm**

- **Response time:**

  - 200 frames/sec with Nematic Twist Liquid Crystal

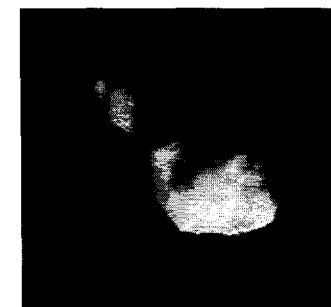 - 2000 frames/sec with Ferroelectric electric Crystal (under development)

Input Spatial Light Modulator
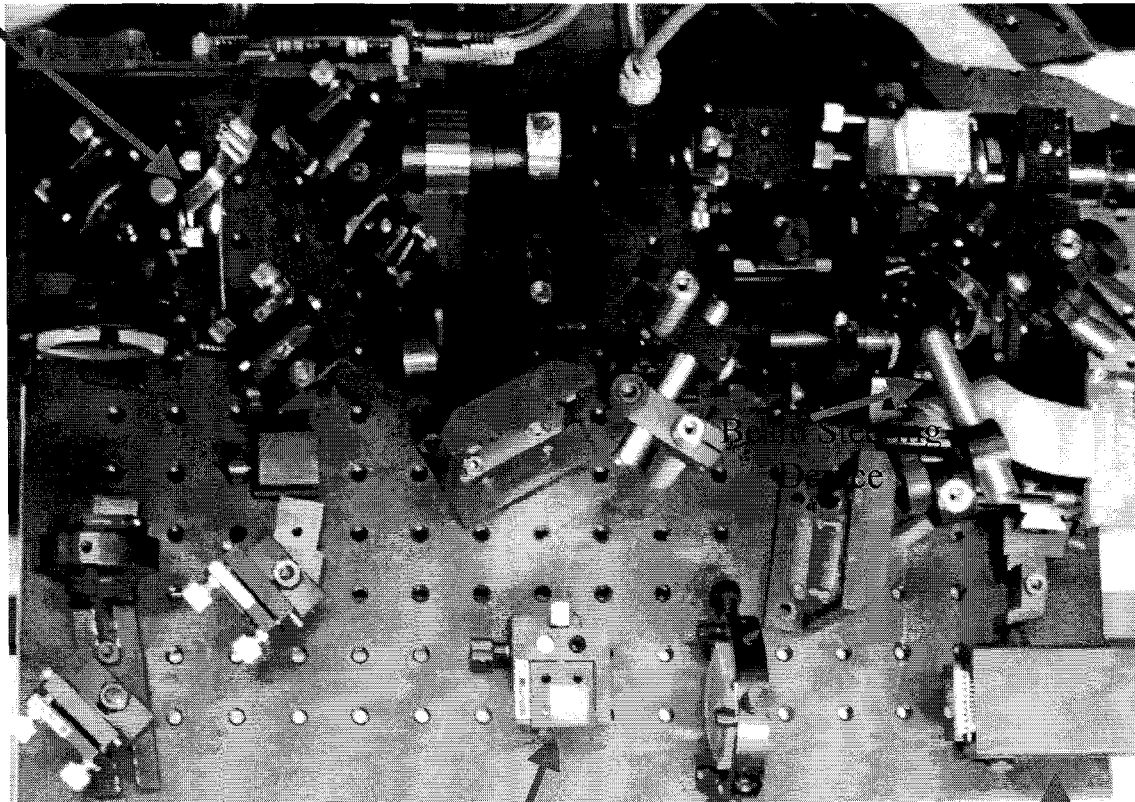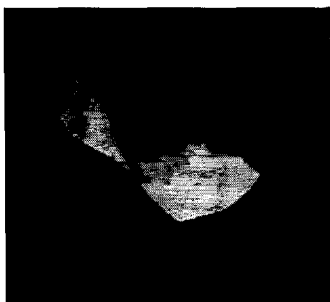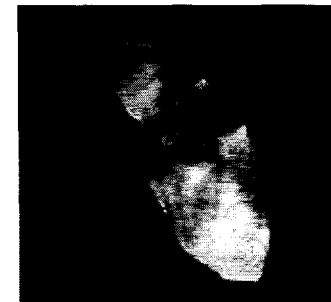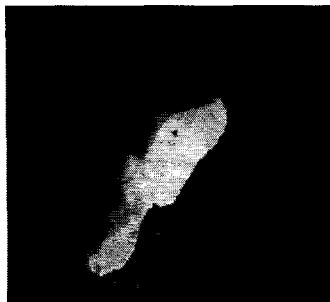

LiNbO$_3$
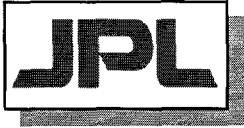**Photorefractive Crystal**

CCD Detector

Photograph of a JPL compact holographic memory breadboard developed under the sponsorship of NASA ESTO

Holographically Retrieved Grayscale Images - Asteroid Toutatis

Experimental results showing retrieved holographic images of a Toutatis Asteroid

Summary and Future Work

- We have developed (with BNS Inc.) a new liquid crystal beam steering device for high-speed, random access beam steering for angularly multiplexed hologram recording
- We have developed a compact CHDS breadboard and demonstrated grayscale holographic data storage/retrieval
- We will continue to integrated a 2-D angularly multiplexing scheme to achieve > 10,000 page of holograms store per PR cube
- We will also started radiation tests of holographic data stored in a $LiNbO_3$ PR crystal
- We will also investigated non-volatile hologram storage using 2-wavelength PR crystal